CSE 331
Software Design and Implementation

Lecture 10
Equality and Hashcode

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Object equality

A simple idea??

- Two objects are equal if they have the same value

A subtle idea: intuition can be misleading

- Same object or same contents?
- Same concrete value or same abstract value?
- Same right now or same forever?
- Same for instances of this class or also for subclasses?
- When are two collections equal?
  - How related to equality of elements? Order of elements?
  - What if a collection contains itself?
- How can we implement equality efficiently?

Expected properties of equality

Reflexive **`a.equals(a) ==  true`**

- Confusing if an object does not equal itself

Symmetric **`a.equals(b)`** $\Leftrightarrow$ **`b.equals(a)`**

- Confusing if order-of-arguments matters

Transitive **`a.equals(b)`** $\wedge$ **`b.equals(c)`** $\Rightarrow$ **`a.equals(c)`**

- Confusing again to violate centuries of logical reasoning

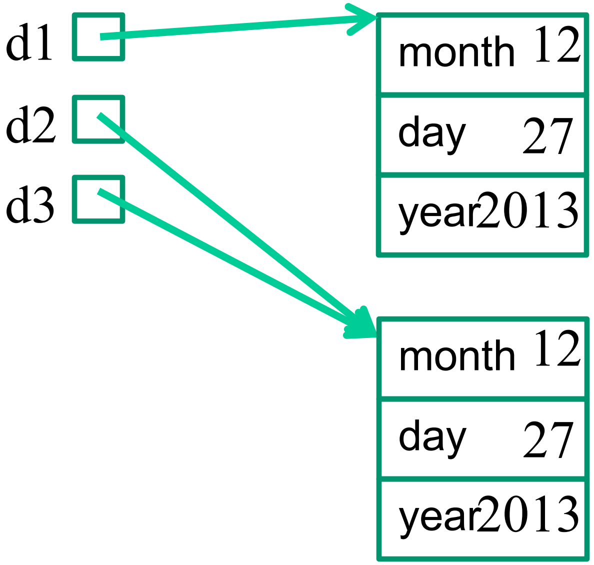
A relation that is reflexive, transitive, and symmetric is an *equivalence relation*

Reference equality

- Reference equality means an object is equal only to itself
  - **`a == b`** only if **`a`** and **`b`** refer to (point to) the same object
- Reference equality is an equivalence relation
  - Reflexive
  - Symmetric
  - Transitive
- Reference equality is the *smallest* equivalence relation on objects
  - "Hardest" to show two objects are equal (must be same object)
  - Cannot be smaller without violating reflexivity
  - Sometimes but not always what we want

What might we want?

```
Date d1 = new Date(12,27,2013);
Date d2 = new Date(12,27,2013);
Date d3 = d2;
// d1==d2 ?
// d2==d3 ?
// d1.equals(d2) ?
// d2.equals(d3) ?
```



- Sometimes want equivalence relation bigger than ==
  - Java takes OOP approach of letting classes *override* **`equals`**

`Object.equals` method

```
public class Object {
  public boolean equals(Object o) {
    return this == o;
  }
  …
}
```

- Implements reference equality
- Subclasses can override to implement a different equality
- But library includes a *contract* **`equals`** should satisfy
  - Reference equality satisfies it
  - So should *any* overriding implementation
  - Balances flexibility in notion-implemented and what-clients-can-assume even in presence of overriding

`equals` specification

`public boolean equals(Object obj)`

Indicates whether some other object is “equal to” this one.

The **`equals`** method implements an equivalence relation:

- It is *reflexive*: for any reference value **`x`**, **`x.equals(x)`** should return **`true`**.
- It is *symmetric*: for any reference values **`x`** and **`y`**, **`x.equals(y)`** should return **`true`** if and only if **`y.equals(x)`** returns **`true`**.
- It is *transitive*: for any reference values **`x`**, **`y`**, and **`z`**, if **`x.equals(y)`** returns **`true`** and **`y.equals(z)`** returns **`true`**, then **`x.equals(z)`** should return **`true`**.
- It is *consistent*: for any reference values **`x`** and **`y`**, multiple invocations of **`x.equals(y)`** consistently return **`true`** or consistently return **`false`**, provided no information used in equals comparisons on the object is modified.
- For any *non-null* reference value **`x`**, **`x.equals(null)`** should return **`false`**.

Why all this?

- Remember the goal is a contract:
  - Weak enough to allow different useful overrides
  - Strong enough so clients can assume equal-ish things
    - Example: To implement a set
  - Complete enough for real software

- So:
  - Equivalence relation
  - Consistency, but allow for mutation to change the answer
  - Asymmetric with **`null`** (other way raises exception)
  - Final detail: argument of **`null`** must return **`false`**

An example

A class where we may want **`equals`** to mean equal contents

```
public class Duration {
    private final int min; // RI: min>=0
    private final int sec; // RI: 0<=sec<60
    public Duration(int min, int sec) {
        assert min>=0 && sec>=0 && sec<60;
        this.min = min;
        this.sec = sec;
    }
}
```

– Should be able to implement what we want and satisfy the **`equals`** contract…

How about this?

```
public class Duration {
    …
    public boolean equals(Duration d) {
        return this.min==d.min && this.sec==d.sec;
    }
}
```

Two bugs:

1. Violates contract for **`null`** (not that interesting)
   – Can add **`if(d==null) return false;`**
      • But our fix for the other bug will make this unnecessary
2. Does not override **`Object`**'s **`equals`** method (more interesting)

Overloading versus overriding

In Java:

- A class can have multiple methods with the same name and different parameters (number or type)
- A method *overrides* a superclass method only if it has the same name and exact same argument types

So **`Duration`**'s **`boolean equals(Duration d)`** does *not* override **`Object`**'s **`boolean equals(Object d)`**

- Sometimes useful to avoid having to make up different method names
- Sometimes confusing since the rules for what-method-gets-called are complicated
- [Overriding covered in CSE143, but not overloading]

Example: *no* overriding

```
public class Duration {
  public boolean equals(Duration d) {…}
  …
}
Duration d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
Object o1 = d1;
Object o2 = d2;
d1.equals(d2); // true
o1.equals(o2); // false(!)
d1.equals(o2); // false(!)
o1.equals(d2); // false(!)
d1.equals(o1); // true [using Object's equals]
```

Example fixed (mostly)

```
public class Duration {
  public boolean equals(Object d) {…}
  …
}
Duration d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
Object o1 = d1;
Object o2 = d2;
d1.equals(d2); // true
o1.equals(o2); // true [overriding]
d1.equals(o2); // true [overriding]
o1.equals(d2); // true [overriding]
d1.equals(o1); // true [overriding]
```

A little more generally

- Won't go through all the *overloading-resolution* rules here

- In short, Java:
  - Uses (compile-time) types to pick the *signature* (at compile-time)
    - In example: if receiver or argument has compile-time type **`Object`**, then only signature taking an **`Object`** is "known to work," so it is picked
  - At run-time, uses dynamic dispatch to choose what implementation with that signature runs
    - In un-fixed example: the inherited method is the only one with the take-an-Object signature
    - In fixed example: Overriding matters whenever the run-time class of the receiver is **`Duration`**

But wait!

This doesn't actually compile:

```
public class Duration {
    …
    public boolean equals(Object o) {
        return this.min==o.min && this.sec==o.sec;
    }
}
```

Really fixed now

```
public class Duration {
   public boolean equals(Object o) {
      if(! o instanceof Duration)
        return false;
      Duration d = (Duration) o;
      return this.min==d.min && this.sec==d.sec;
   }
}
```

- Cast cannot fail
- We want equals to work on *any* pair of objects
- Gets **`null`** case right too (**`null instanceof C`** always **`false`**)
- So: rare use of cast that is correct and idiomatic
  - This is what you should do (cf. *Effective Java*)

Satisfies the contract

```
public class Duration {
    public boolean equals(Object o) {
        if(! o instanceof Duration)
          return false;
        Duration d = (Duration) o;
        return this.min==d.min && this.sec==d.sec;
    }
}
```

- Reflexive: Yes
- Symmetric: Yes, even if **`o`** is not a **`Duration`**!
  - (Assuming **`o`**'s **`equals`** method satisfies the contract)
- Transitive: Yes, similar reasoning to symmetric

Even better

- Great style: use the **`@Override`** annotation when overriding

```
public class Duration {
    @Override
    public boolean equals(Object o) {
        …
    }
}
```

- *Compiler warning* if not actually an override
  - Catches bug where argument is **`Duration`** or **`String`** or ...
  - Alerts reader to overriding
    - Concise, relevant, *checked* documentation

Okay, so are we done?

- Done:
  - Understanding the **`equals`** contract
  - Implementing **`equals`** correctly for **`Duration`**
    - Overriding
    - Satisfying the contract [for all types of arguments]

- Alas, matters can get worse for subclasses of **`Duration`**
  - No perfect solution, so understand the trade-offs…

Two subclasses

```
class CountedDuration extends Duration {
  public static numCountedDurations = 0;
  public CountedDuration(int min, int sec) {
    super(min,sec);
    ++numCountedDurations;
  }
}
class NanoDuration extends Duration {
  private final int nano;
  public NanoDuration(int min, int sec, int nano){
    super(min,sec);
    this.nano = nano;
  }
  public boolean equals(Object o) { … }
  …
}
```

`CountedDuration` is good

- `CountedDuration` does not override `equals`
- Will (implicitly) treat any `CountedDuration` like a `Duration` when checking `equals`
- Any combination of `Duration` and `CountedDuration` objects can be compared
  - Equal if same contents in `min` and `sec` fields
  - Works because `o instanceof Duration` is `true` when `o` is an instance of `CountedDuration`

Now **`NanoDuration`** [not so good!]

- If we don't override **`equals`** in **`NanoDuration`**, then objects with different **`nano`** fields will be equal

- So using everything we have learned:

```
@Override
public boolean equals(Object o) {
  if (! (o instanceof NanoDuration))
    return false;
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

- But we have violated the **`equals`** contract
  - Hint: Compare a **`Duration`** and a **`NanoDuration`**

The symmetry bug

```
public boolean equals(Object o) {
  if (! (o instanceof NanoDuration))
    return false;
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

This is ***not symmetric***!

```
Duration d1 = new NanoDuration(5, 10, 15);
Duration d2 = new Duration(5, 10);
d1.equals(d2); // false
d2.equals(d1); // true
```

Fixing symmetry

This version restores symmetry by using **`Duration`**'s **`equals`** if the argument is a **`Duration`** (and not a **`NanoDuration`**)

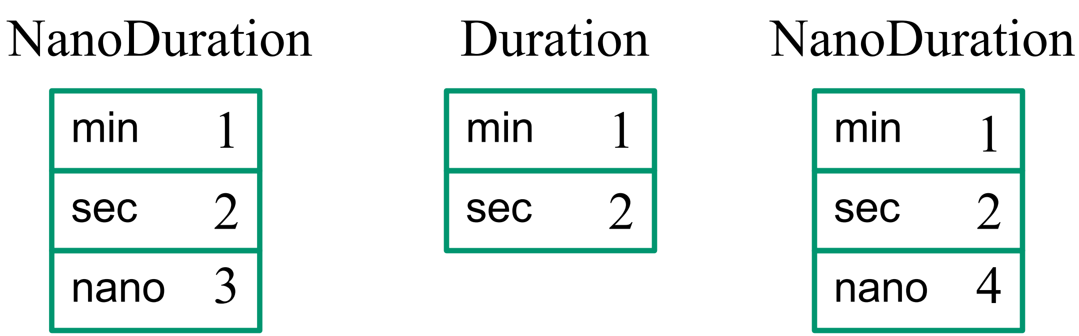
```
public boolean equals(Object o) {
  if (! (o instanceof Duration))
    return false;
  // if o is a normal Duration, compare without nano
  if (! (o instanceof NanoDuration))
    return super.equals(o);
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

Alas, this *still* violates the **`equals`** contract

- Transitivity…

The transitivity bug

```
Duration d1 = new NanoDuration(1, 2, 3);
Duration d2 = new Duration(1, 2);
Duration d3 = new NanoDuration(1, 2, 4);
d1.equals(d2);   // true
d2.equals(d3);   // true
d1.equals(d3);   // false!
```



No great solution

- *Effective Java* says not to (re)override **`equals`** like this
  - Unless superclass is non-instantiable (e.g., abstract)
  - "Don't do it" a non-solution given the equality we want for **`NanoDuration`** objects

- Two far-from-perfect approaches on next two slides:
  1. Don't make **`NanoDuration`** a subclass of **`Duration`**
  2. Change **`Duration`**'s **`equals`** such that only **`Duration`** objects that are not (proper) subclasses of **`Duration`** are equal

Avoid subclassing

Choose composition over subclassing

- Often good advice: many programmers overuse (abuse) subclassing [see future lecture on proper subtyping]

```
public class NanoDuration {
  private final Duration duration;
  private final int nano;
  …
}
```

`NanoDuration` and **`Duration`** now unrelated

- No presumption they can be compared to one another

Solves some problems, introduces others

- Can't use **`NanoDuration`**s where **`Duration`**s are expected (not a subtype)
- No inheritance, so need explicit *forwarding* methods

Slight alternative

- Can avoid some method redefinition by having **`Duration`** and **`NanoDuration`** both extend a common abstract class
  - Or implement the same interface
  - Leave overriding **`equals`** to the two subclasses

- Keeps **`NanoDuration`** and **`Duration`** from being used “like each other”

- But requires advance planning or willingness to change **`Duration`** when you discover the need for **`NanoDuration`**

The `getClass` trick

Different run-time class checking to satisfy the **`equals`** contract:

```
@Overrides
public boolean equals(Object o) { // in Duration
  if (o == null)
    return false;
  if (! o.getClass().equals(getClass()))
    return false;
  Duration d = (Duration) o;
  return d.min == min && d.sec == sec;
}
```

But now **`Duration`** objects never equal **`CountedDuration`** objects

- Subclasses do not “act like” instances of superclass because behavior of **`equals`** changes with subclasses
- Generally considered wrong to “break” subtyping like this

Subclassing summary

- Due to subtleties, no perfect solution to how to design and implement **`NanoDuration`**

- Unresolvable tension between
  - "What we want for equality"
  - "What we want for subtyping"

- Now:
  - **`Duration`** *still* does not satisfy contracts relevant to **`equals`**
  - Have to discuss another **`Object`** method: **`hashCode`**

hashCode

Another method in **`Object`**:

`public int hashCode()`

"Returns a hash code value for the object. This method is supported for the benefit of hashtables such as those provided by **`java.util.HashMap`**."

Contract (again essential for correct overriding):

- Self-consistent:

  `o.hashCode() == o.hashCode()`

  ...so long as **`o`** doesn't change between the calls
- Consistent with equality:

  `a.equals(b)` $\Rightarrow$ **`a.hashCode() == b.hashCode()`**

Think of it as a pre-filter

- If two objects are equal, they *must* have the same hash code
  - Up to implementers of **`equals`** and **`hashCode`** to satisfy this
  - If you override **`equals`**, you ***must*** override **`hashCode`**

- If two objects have the same hash code, they *may or may not* be equal
  - “Usually not” leads to better performance
  - **`hashCode`** in **`Object`** tries to (but may not) give every object a different hash code

- Hash codes are usually cheap[er] to compute, so check first if you “usually expect not equal” – a pre-filter

Asides

- Hash codes are used for hash tables
  - A common collection implementation
  - See CSE332
  - Libraries won’t work if your classes break relevant contracts

- Cheaper pre-filtering is a more general idea
  - Example: Are two large video files the exact same video?
    - Quick pre-filter: Are the files the same size?

Doing it

- So: we have to override **`hashCode`** in **`Duration`**
  - Must obey contract
  - Aim for non-equals objects usually having different results

- Correct but expect poor performance:

```
public int hashCode() { return 1; }
```

- Correct but expect better-but-still-possibly-poor performance:

```
public int hashCode() { return min; }
```

- Better:

```
public int hashCode() { return min ^ sec; }
```

Correctness depends on `equals`

Suppose we change the spec for **`Duration`**'s **`equals`**:

```
// true if o and this represent same # of seconds
public boolean equals(Object o) {
  if (! (o instanceof Duration))
    return false;
  Duration d = (Duration) o;
  return 60*min+sec == 60*d.min+d.sec;
}
```

Must update **`hashCode`** – why?

- This works:

```
public int hashCode() {
  return 60*min+sec;
}
```

Equality, mutation, and time

If two objects are equal now, will they always be equal?

- In mathematics, “yes”
- In Java, “you choose”
- `Object` contract doesn't specify

For immutable objects:

- Abstract value never changes
- Equality should be forever (even if rep changes)

For mutable objects, either:

- Stick with reference equality
- “No” equality is not forever
  - Mutation changes abstract value, hence what-object-equals

Examples

`StringBuffer` is mutable and sticks with reference-equality:

```
StringBuffer s1 = new StringBuffer("hello");
StringBuffer s2 = new StringBuffer("hello");
s1.equals(s1); // true
s1.equals(s2); // false
```

By contrast:

```
Date d1 = new Date(0); // Jan 1, 1970 00:00:00 GMT
Date d2 = new Date(0);

d1.equals(d2); // true
d2.setTime(1);
d1.equals(d2); // false
```

Behavioral and observational equivalence

Two objects are "behaviorally equivalent" if there is no sequence of operations (excluding ==) that can distinguish them

Two objects are "observationally equivalent" if there is no sequence of *observer* operations that can distinguish them

- Excludes mutators (and ==)

Equality and mutation

`Date` class implements (only) observational equality

Can therefore violate rep invariant of a **`Set`** by mutating after insertion

```
Set<Date> s = new HashSet<Date>();
Date d1 = new Date(0);
Date d2 = new Date(1000);
s.add(d1);
s.add(d2);
d2.setTime(0);
for (Date d : s) { // prints two of same date
    System.out.println(d);
}
```

Pitfalls of observational equivalence

Have to make do with caveats in specs:

> *"Note: Great care must be exercised if mutable objects are used as set elements. The behavior of a set is not specified if the value of an object is changed in a manner that affects equals comparisons while the object is an element in the set."*

Same problem applies to keys in maps

Same problem applies to mutations that change hash codes when using **`HashSet`** or **`HashMap`**

(Libraries choose not to copy-in for performance and to preserve object identity)

Another container wrinkle: self-containment

equals and **hashCode** on containers are recursive:

```
class ArrayList<E> {
  public int hashCode() {
     int code = 1;
     for (Object o : list)
       code = 31*code + (o==null ? 0 : o.hashCode());
    return code;
  }
```

This causes an infinite loop:

```
List<Object> lst = new ArrayList<Object>();
lst.add(lst);
lst.hashCode();
```

Summary

- Different notions of equality:
  - Reference equality stronger than
  - Behavioral equality stronger than
  - Observational equality

- Java's **`equals`** has an elaborate specification, but does not require any of the above notions
  - Also requires consistency with **`hashCode`**
  - Concepts more general than Java

- Mutation and/or subtyping make things even less satisfying
  - Good reason not to overuse/misuse either